CVD POLYCRYSTALLINE DIAMOND HIGH-Q MICROMECHANICAL RESONATORS

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ABSTRACT

Chemical **V**apor **D**eposited (CVD) polycrystalline diamond material, with an acoustic velocity higher than that of polycrystalline silicon, has been utilized as the structural material for clamped-clamped beam (CC-beam) micromechanical resonators with measured resonance frequencies from 2.7 MHz to 9.8 MHz, and Q's up to 6,225—easily on par with that of previous polysilicon resonators in this frequency range. In addition to CC-beams, CVD polydiamond folded-beam μmechanical resonators are also demonstrated with Q's in the range of 20,000. With its higher acoustic velocity, polydiamond has great potential for more easily achieving the coveted UHF frequencies (0.3-3GHz) required for use in wireless communication transceivers.

I. INTRODUCTION

Recent demonstrations of polysilicon vibrating micromechanical ("μmechanical") resonators with frequencies in the hundreds of MHz that retain Q's around 10,000 [1] are now infusing new vigor into research efforts aimed at further extending their frequency range into the high-UHF and S-Band ranges needed for front-end RF applications in today's wireless transceivers. To date, several approaches to increasing frequency have been successfully demonstrated, including: (1) brute force scaling of devices to smaller and smaller dimensions [2]; (2) the use of strategic geometries to take advantage of higher frequency mode shapes and to eliminate Q-degradation due to anchor losses [1]; and (3) the use of alternative materials, such as SiC [3], to boost the acoustic velocity of the resonator structural material, thereby making it easier to achieve higher frequency without the need for overly tiny dimensions. Due to the possibility of "scaling-induced" performance degradation [4], of the above techniques, (2) and (3) show the most promise for extending μmechanical resonator frequency range while retaining the Q's and the degree of stability needed for application to the low-loss bandpass filters and ultra-stable reference oscillators needed in communication transceivers [5].

This work investigates one variant of approach (3), in which CVD polycrystalline diamond material, with an acoustic velocity potentially more than 2X higher than that of polycrystalline silicon, is utilized as the structural material for clamped-clamped beam (CC-beam) and folded-beam μmechanical resonators. Since the resonance frequency of a mechanical resonator is generally directly proportional to the acoustic velocity of its structural material, polydiamond has great potential for more easily achieving the coveted UHF frequencies (0.3-3GHz) required for use in present and future wireless communication transceivers. In addition, due to the inherent stability and chemical inertness of diamond material [6], diamond can potentially offer better aging characteristics than polysilicon, which is paramount for frequency reference applications. Finally, as demonstrated in this work, polydiamond can be machined nearly as easily as polysilicon, making it amenable to conventional surface micromachining, and with deposition temperatures below 600^{o}C, CVD polydiamond can be more easily integrated with highly conductive metal electrodes to allow lower losses and higher power handling at GHz frequencies.

In this initial work, CVD polydiamond CC-beam μmechanical resonators are demonstrated with measured resonance frequencies from 2.7 MHz to 9.8 MHz, and Q's up to 6,225—easily on par with that of previous polysilicon resonators in this frequency range. In addition, ~39 kHz folded-beam, comb-driven resonators are demonstrated with Q's in the range of 20,000. The frequencies seen in these polydiamond devices are 15% higher than that of equivalently sized polysilicon versions, which is not the 2X potentially achievable, but which encourages further work in this area.

II. MATERIAL-DEPENDENCE OF THE RESONANCE FREQUENCY

For a CC-beam (such as in Fig. 4(a)), if its length is much longer than its width or thickness, Euler-Bernoulli theory is sufficiently accurate for determination of its resonance frequency, given by the expression [7]

$$f_o = 1.03\kappa\sqrt{\frac{E}{\rho}}\frac{h}{L_r^2}[1 - g(d, V_P)]^{1/2} \tag{1}$$

which clearly depends on both beam dimensions (specified in Fig. 4(a)) and structural material properties, specifically the Young's modulus E and the density ρ, both of which define the acoustic velocity, $\sqrt{E/\rho}$. In (1), κ is a frequency modification factor that accounts for beam topography [7], and the function g accounts for the effect of electrical stiffness [7].

Folded-beam, comb-driven μmechanical resonators, also used in this work, show a similar proportional dependence on acoustic velocity, with resonance frequency given by [8]

$$f_o = \frac{1}{2\pi}\sqrt{\frac{E}{\rho}}\left[\frac{2h(W_{fb}/L_{fb})^3}{\left(V_p + \frac{1}{4}V_t + \frac{12}{35}V_b\right)}\right]^{1/2} \tag{2}$$

where W_{fb} and L_{fb} are the width and length, respectively, of the folded-beam suspensions; h is thickness; and V_p, V_t, and V_b are the volumes of the plate, the combined folding trusses, and the combined folded-beams, respectively.

Given the influence of material properties on resonance fre-

Table 1: Comparison of Structural Materials

Property	polySi	SiC	Diamond	Units
Density, ρ	2,300	3,300	3,500	kg/m^3
Young's Modulus, E	150	448 [3]	1,200 [6]	GPa
Acoust. Velocity, $\sqrt{E/\rho}$	8,075	11,652	18,516	m/s
Normalized Acoust. Vel.	1	1.44	2.29	—

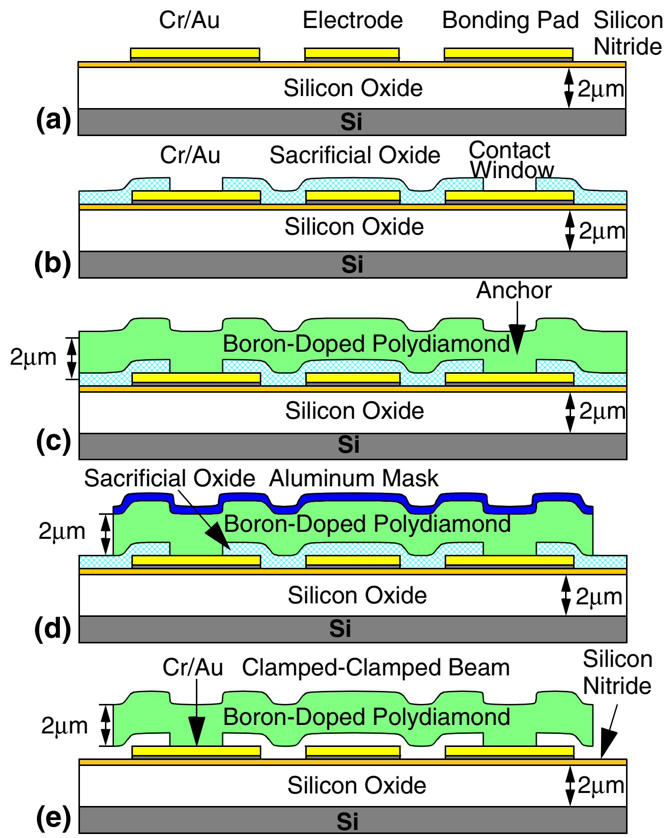

Fig. 1: Fabrication process flow for the polycrystalline diamond CC-beam resonator with metal electrodes.

quency, Table 1 compares the material properties of LPCVD polycrystalline silicon and two high acoustic velocity material contenders: single-crystal diamond and silicon carbide. Of these materials, diamond clearly has the most potential for attaining the frequency extension required for RF applications.

III. DIAMOND MICROMECHANICAL RESONATOR PROCESS TECHNOLOGY

Figure 1 presents step-by-step process cross-sections summarizing the complete fabrication process flow for CVD polydiamond μmechanical resonators, with the final cross-section shown in Fig. 1(e). This process differs from conventional polysilicon surface micromachining processes [7] in three key ways: (1) Cr/Au metal is used as the interconnect material rather than polysilicon, to lower interconnect losses for high frequency applications; (2) PECVD oxide is used as the sacrificial layer, which simplifies the release of sub-μm electrode-to-resonator gaps; and (3) low temperature CVD polydiamond is used as the structural material, with advantages as described above.

Interconnect Layers.

The process begins with blanket depositions of oxide and nitride isolation layers, 2 and 0.3 μm-thick, respectively. A Cr/Au film is then deposited and patterned via lift-off to form metal electrodes and interconnects for eventual devices (Fig. 1(a)). Next, a 3000Å film of PECVD oxide is deposited at 200°C to serve as a sacrificial layer to be removed at the end of the process, but that temporarily supports eventual diamond devices during their own deposition and patterning. PECVD oxide is used in this process rather than the more conventional LTO or HTO with the intent of keeping the total temperature budget low enough to allow later integration of MEMS and transistor circuits via post-transistor processing [8]. After opening anchors using RIE (Fig. 1(b)), the wafers are ready for CVD diamond deposition.

CVD Diamond Deposition.

Among the various steps in any CVD polydiamond process, the formation of a diamond nucleation layer is perhaps the most important, since the size and density of nucleation particles has the greatest impact on the eventual size and coverage of diamond grains, hence, on the surface roughness of polydiamond films. Given the impact of surface roughness on the Q of previous high frequency polysilicon micromechanical resonators [9], smooth films are preferred.

For this work, a nucleation layer was established by (1) first pretreating the substrate to the diamond growth plasma conditions for a brief period of time, typically 10 to 30 minutes; then (2) putting the treated substrate into an ultrasonic bath of ultra disperse nanocrystalline diamond powder [10] in methanol for 10 to 60 minutes; followed by (3) immediate rinsing and washing with ethanol and nitrogen blow dry. Finally, the seeded substrate is returned to the growth reactor and doped diamond is grown to the desired thickness. Doping was achieved by the addition of dilute amounts of diborane to the reactants. The growth rate and film thickness was monitored *in situ* by diode laser reflectometry at 670 nm. Uniform and conformal nucleation densities in excess of 10^{11} cm^{-2} have been observed over a variety of dissimilar materials with this technique, enabling the fabrication of continuous films with thicknesses as little as 80 to 100 nm on Si or SiO_2.

The films were grown in a commercial microwave plasma reactor, shown schematically in Fig. 2, (Model PDS-17, Astex Inc., Woburn, MA) operating at 2.45 GHz with a maximum power of 1.5 kW. Purified hydrogen, methane (99.999%), and diborane were used as reactants. The substrate was placed on an inductively heated susceptor and the pressure of the flowing gases was maintained at 15 Torr.

Etching Diamond.

After deposition of 1.1 μm of polydiamond, a 4,000Å-thick Al film is then evaporated onto the diamond, then patterned via lift-off to define μmechanical resonator geometries (both CC-beams and folded-beam resonators). Using the Al as a hard etch mask, the exposed diamond is then etched via an RIE recipe using 40 sccm O_2 and 1 sscm CF_4 at 50 mTorr with a power of 250 W, with a diamond etch rate of about 2 μm/h. This particular etch recipe also etched the underlying PECVD sacrificial oxide layer at a rate of 0.15 μm/h, which limited the allowable

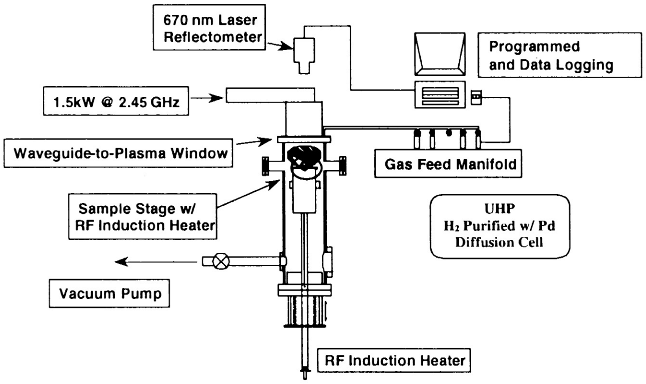

Fig. 2: Schematic of the microwave PECVD reactor used for polydiamond deposition.

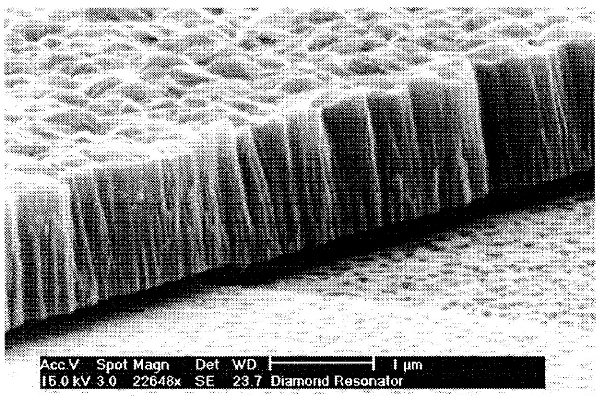

Fig. 3: Zoom-in SEM on the edge of a 3MHz CVD polydiamond CC-beam µmechanical resonator with metal electrodes, showcasing fairly well-defined sidewalls.

overetch time, and which may become a problem in the future for structures with larger topographies, where stringers must be removed. Nevertheless, this etch recipe yielded very good results, with well-defined sidewalls, as shown in the SEM of Fig 3.

After patterning the CVD polydiamond, the Al etch mask and sacrificial oxide layers are removed in a solution of buffered hydrofluoric acid, which frees diamond structures without attacking either diamond or Cr/Au metal interconnect layers, yielding free-standing structures ready for testing. Figs. 4(a) and 4(b) present SEMs of a 55 µm-long, 3 MHz, CVD polydiamond CC-beam resonator and a 38.8 kHz folded-beam, comb-driven µmechanical resonator, respectively, all fabricated via the process of Fig. 1.

IV. EXPERIMENTAL RESULTS

CC-beams were designed and fabricated with varying lengths with the intention of generating a plot of frequency versus beam length, from which the Young's modulus can be more accurately extracted by curve fitting. Table 2 summarizes the geometric design variants used, showing beam lengths from 29 to 55 µm. In addition, folded-beam comb-driven resonators were fabricated, also capable of yielding Young's modulus data, but with the main purpose of establishing a more accurate value for the Q of this polydiamond material. In particular, although

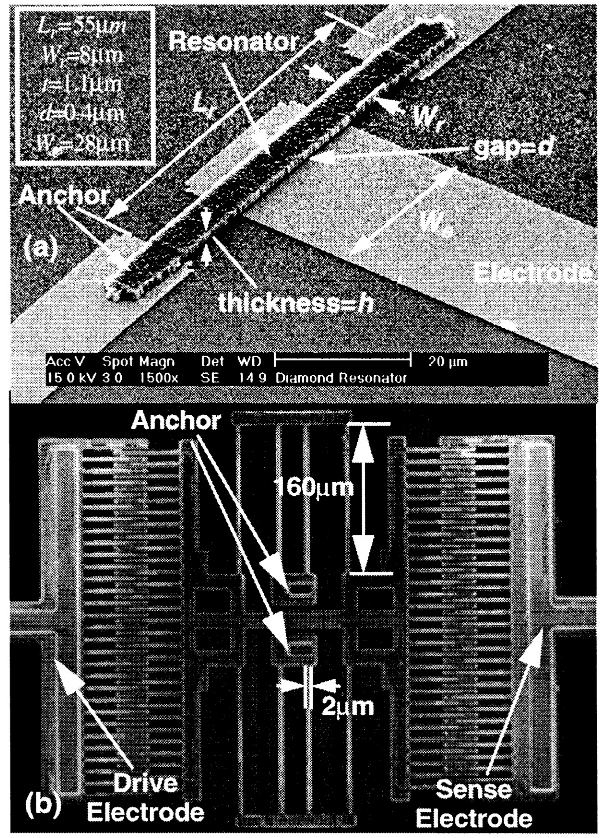

Fig. 4: SEMs of (a) a 3 MHz CVD polydiamond CC-beam with metal electrodes fabricated via the process of Fig. 1; and (b) a 38.8 kHz folded-beam, comb-driven µmechanical resonator.

TABLE 2. CC-Beam Design/Performance Summary

	Frequency [MHz]			
Parameter	**3**	**4.2**	**10**	**Units**
Length, L_r	55	45	29	µm
Width, W_r	8	8	8	µm
Thickness, h	1.1	1.1	1.1	µm
Young's Modulus, E	304	304	304	GPa
Density, ρ	3,500	3,500	3,500	kg/m^3
Measured f_o	3.022	4.206	9.79	MHz
Calculated f_o	2.875	4.413	10.535	MHz
Quality Factor, Q	6,225	2,071	1,037	—

CC-beams can achieve higher frequencies than folded-beam resonators, they unfortunately begin to exhibit significant losses to anchors as frequencies rise, so the Q's measured on CC-beams are more indicative of anchor losses than intrinsic material losses. As a result, lower frequency folded-beam resonators are better gauges for material losses.

Upon testing, the CVD diamond folded-beam resonators of this particular run were found to be more resilient against moisture-induced stiction than previous polysilicon versions, and supercritical CO_2 drying was not necessary to obtain free-standing structures; i.e., no devices were stuck after a simple hot-

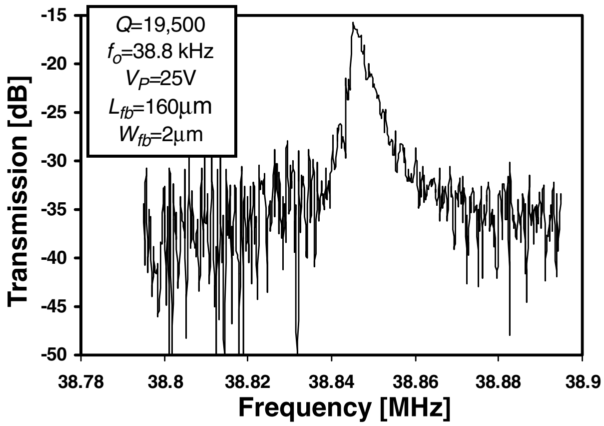

Fig. 5: Frequency characteristic for a 38.8 kHz CVD polydiamond folded-beam µmechanical resonator.

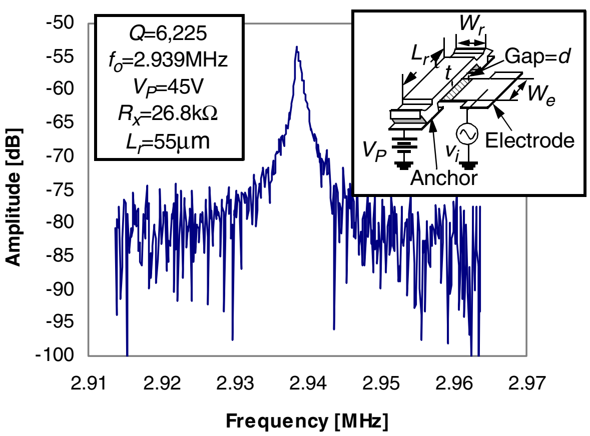

Fig. 6: Frequency characteristic for a 2.94 MHz CVD polydiamond CC-beam resonator

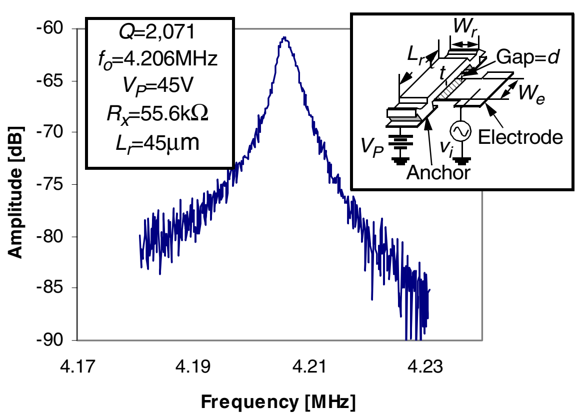

Fig. 7: Frequency characteristic for a 4.21 MHz CVD polydiamond CC-beam resonator.

plate-assisted air drying step. Figure 5 presents the measured frequency characteristic for a 38.8 kHz folded-beam resonator, showing a Q of 19,500, which almost as good as values seen in identical polysilicon µmechanical resonators. This makes polydiamond a good material candidate for use in high-Q filter and oscillator applications for communications, as well as other high-Q applications (e.g., gyroscopes, resonant sensors, etc.).

Figures 6 and 7 present the frequency characteristics for 2.94

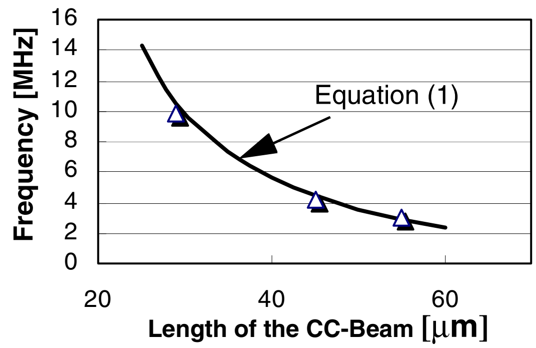

Fig. 8: Plot of frequency versus beam length for the CVD diamond resonators of this work. (The points are measured data; the curve is the theoretical prediction of Eq. (1).

and 4.21 MHz CC-beams, respectively, measured under 50 mTorr pressure, showing Q's of ~6,000 and ~2,000, both of which are comparable to values seen in polysilicon versions at similar frequencies. Figure 8 presents the desired plot of frequency versus beam length, from which a curve fit of Eq. (1) (shown) using the crystalline diamond density of 3,500 kg/m^3, yields a Young's modulus of 304 GPa and an acoustic velocity of 9,320 m/s. Although this value of acoustic velocity is larger than the 8,076 m/s of polysilicon (by 15%), it is still not as large as potentially achievable, since single-crystal diamond has an acoustic velocity more than twice that of polysilicon. Future process development with better control of polycrystalline grain size will likely be needed to achieve a polycrystalline acoustic velocity closer to that of single-crystal diamond.

V. CONCLUSION

Both clamped-clamped beam and folded-beam µmechanical resonators using CVD polydiamond as their structural material have been successfully demonstrated with frequencies 15% higher than that of equivalently sized polysilicon versions, and with Q's up to 20,000, which is on par with polysilicon devices. Although not as large as the doubling in frequency potentially achievable, this 15% increase does encourage further refinements in the CVD polydiamond deposition process to further raise the material acoustic velocity. If achievable, then this, together with some initial evidence that polydiamond devices are more robust than polysilicon counterparts (e.g., w/ respect to stiction), make polydiamond a strong material contender for future RF MEMS devices.

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